ENCODERS FOR DELTAMODULATION TRANSMISSION SYSTEMS

ROBERT IRVING

ENCODERS FOR DELTAMODULATION TRANSMISSION SYSTEMS

-

Robert Irving

ENCODERS FOR DELTAMODULATION

TRANSMISSION SYSTEMS

by

Robert Irving
Lieutenant, United States Navy

Submitted in partial fulfillment
of the requirements
for the degree of
MASTER OF SCIENCE
IN
ENGINEERING ELECTRONICS

UNITED STATES NAVAL POSTGRADUATE SCHOOL
Monterey, California

1954

This work is accepted as fulfilling

the thesis requirements for the degree of

MASTER OF SCIENCE

IN

ENGINEERING ELECTRONICS

from the

United States Naval Postgraduate School

PREFACE

Deltamodulation is a transmission system of relatively recent origin which holds forth a promise of being able to combine the tremendous signal-to-noise ratio improvement of the pulse-code modulation systems with a simplicity of equipment comparable to that involved in amplitude-modulation telephony. This paper is the result of an attempt to compile and evaluate all of the currently published modulator circuits, plus several rather elementary modulators envisioned by the author. This work was done during the academic year 1953 at the United States Naval Postgraduate School.

The author would like to take this opportunity to express his gratitude to Professor Earl G. Goddard for suggestion of the topic and for encouragement towards completion of the paper.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

TABLE OF SYMBOLS AND ABBREVIATIONS

SYMBOLS

$F(t)$	A General Continuous Function of Time	
f_{max}	Highest Frequency of the Variable-Frequency Pulse Generator under Maximum Modulation Conditions	
C	Capacitor	Subscripts used to differentiate between different elements of the same type
R	Resistor	
V	Vacuum Tube	
T	Transformer	
D	Crystal Diode	

ABBREVIATIONS

Kohm	Kilohm (one thousand ohms)
Kc.	Kilocycle (one thousand cycles per second)

SUMMARY

Deltamodulation is defined and a brief comparison is made between deltamodulation and the other pulse code modulation systems with respect to sampling rate and bandwidth. The operation of a deltamodulation system is outlined, and the implications of quantization as applied to a deltamodulation signal are discussed. The manner in which a Feedback Method encoder operates and five modulators using this method are analyzed, with the advantages and disadvantages of each equipment. The Synthesis Method of encoding, and the only modulator developed to date to take advantage of this method, are analyzed. A comparison between all modulators discussed is made, leading to the conclusion that the modulator using the Synthesis Method is superior to all others included in this paper.

CHAPTER I

PRINCIPLES OF DELTAMODULATION

Deltamodulation may be described as a system of pulse code modulation in which the coding takes the form of the presence or absence of each individual pulse in a time sequence of equally spaced pulses of equal amplitude. In common with the other systems of pulse code modulation, deltamodulation is a quantized system, each pulse (or absence of pulse) representing a finite and constant increment in the value of the coded function. From this fact and the common mathematical use of the symbol "delta" to represent an increment, it is not difficult to deduce the origin of the term <u>delta</u>modulation. Due to its incremental nature, deltamodulation has a distinct disadvantage when compared to other pulse code modulation systems; in order to reproduce a given waveform with a given degree of fidelity, the sampling rate for deltamodulation must be many times higher than that of an equivalent pulse code modulation system, being of the order of twelve times as high.[5] In order to reproduce a voice signal with frequency components up to 3000 cycles per second, it is common practice to use a sampling rate of approximately 8000 cycles per second for pulse code modulation.[1,4] Thus to produce the same fidelity of reproduction using deltamodulation, it would be necessary to use a sampling rate of very nearly 100 Kc. It has been shown,[2,5] however, due to the difference in the number of pulses per sample, that the bandwidth of deltamodulation is only about 50% wider than that of an equivalent pulse code system.

For example, consider a pulse code modulation system using a 7-unit code at an 8 Kc. sampling rate, and an equivalent[5] deltamodulation system using a 100 Kc. sampling rate. The pulse code system would require a maximum of 56 pulses per millisecond, and the deltamodulation system a maximum of 100 pulses per millisecond, giving a rough correlation with the 50%' difference in bandwidths predicted. In practice the bandwidth of the pulse code system would be wider than 56 Kc., since the pulses must be made narrower to place them in the binary groups. The delta-modulation pulses require no grouping, and may be as wide as one-half the sampling period, resulting in the 100 Kc. being the maximum required bandwidth for a single channel. Limiting the highest modulating frequency to 3 Kc. (communication quality voice transmission) would allow for a minimum of 33 deltamodulation signals per cycle of the modulation. This would limit the number of quantized levels at 3 Kc. to about 15, whereas the 7-unit code would provide 128 quantized levels independent of frequency. The noise introduced by quantizing the signal is an inverse function of the number of quantizing levels. It would appear as a result that the quantizing noise in the deltamodulation system would be much greater than that in the equivalent pulse code modulation system. However, the amplitude of the individual frequency components of speech decrease with increasing frequency, hence with the pulse code system set for 128 levels at the amplitude of the low-frequency components, it will be unable to provide more than a small fraction of that number at the upper limit of modulation. It is also to be noted that the number of permissable quantizing levels increases as frequency decreases in the deltamodulation system. Thus the two systems have the same order of quantizing noise.

The major advantage of the deltamodulation system over other methods of pulse code modulation lies in the simplicity of the terminal equipment required to encode and decode the signals. In its simplest form the decoding equipment may consist of nothing more complex than an integrating network and a low-pass filter, and in the case of wire transmission over short distances the entire receiver might be embodied in these two elements. In more complex systems the deltamodulation signal could be transmitted as a pulsed signal in any of the usual transmission mediums: video cable, sonic carrier, radio-frequency carrier, modulated light signal, etc. In this case the received signal would be amplified (if necessary) and detected by a converter suitable to the medium chosen, and the detected pulse signals applied to the integrating network. It is therefore apparent that in order to apply deltamodulation to any of the presently used communication systems having the necessary bandwidth available, it is necessary only to have a coder at the transmitter and a decoder at the receiver, the other needed elements being contained within the system already in operation. In order to more nearly realize the very large signal-to-noise ratios possible with deltamodulation or any other type of pulse code modulation, a pulse regeneration circuit should be used in the receiver. However, since this is equally true for all other types of pulse code modulation, this does not reduce the advantages obtained by deltamodulation with regard to the simplicity of the encoder and decoder required.

It is the purpose of this paper to describe and evaluate some of the various methods of producing the encoded deltamodulation signal for transmission in the medium chosen. In the following discussion of

encoders the type of deltamodulation which uses the single-integrating decoding network will be considered exclusively, since it is in this type that the greatest amount of developmental work has been done.

In the majority of the theoretical treatments of deltamodulation[5,7,9] the signal is considered to consist of positive and negative pulses of equal amplitude, representing respectively an increase and a decrease in the value of the function encoded. These polarized pulses are then applied to an integrating network, producing a step approximation to the value of the coded function, and a following low-pass filter smooths this to an audio signal, as shown in figure 1. Use of the polar pulse method in a practical transmission system would entail the use of positive and negative modulation of a carrier, and the average energy transmitted would be very high, being nearly the same as the energy transmitted in an unmodulated C.W. signal. It is obvious that in a system using the polar pulses, a very large percentage of the energy transmitted would contain no information, and hence would be wasted energy as far as the communication system is concerned. As a result, most practical deltamodulation systems use a transmitted signal consisting only of pulses corresponding to the positive pulses of the polar pulse method, with no signals being transmitted between these pulses, as shown in figure 2.

The equivalence of the polar pulse method to the method using the presence or absence of the pulse may be easily demonstrated. Consider figure 1(b). If the level of each pulse were to be increased by one unit, the signal would be converted to a series of pulses of amplitudes 2 and 0, as shown in figure 2(a). If further, the "integrating" network is so modified that the level of charge falls by one unit during the time

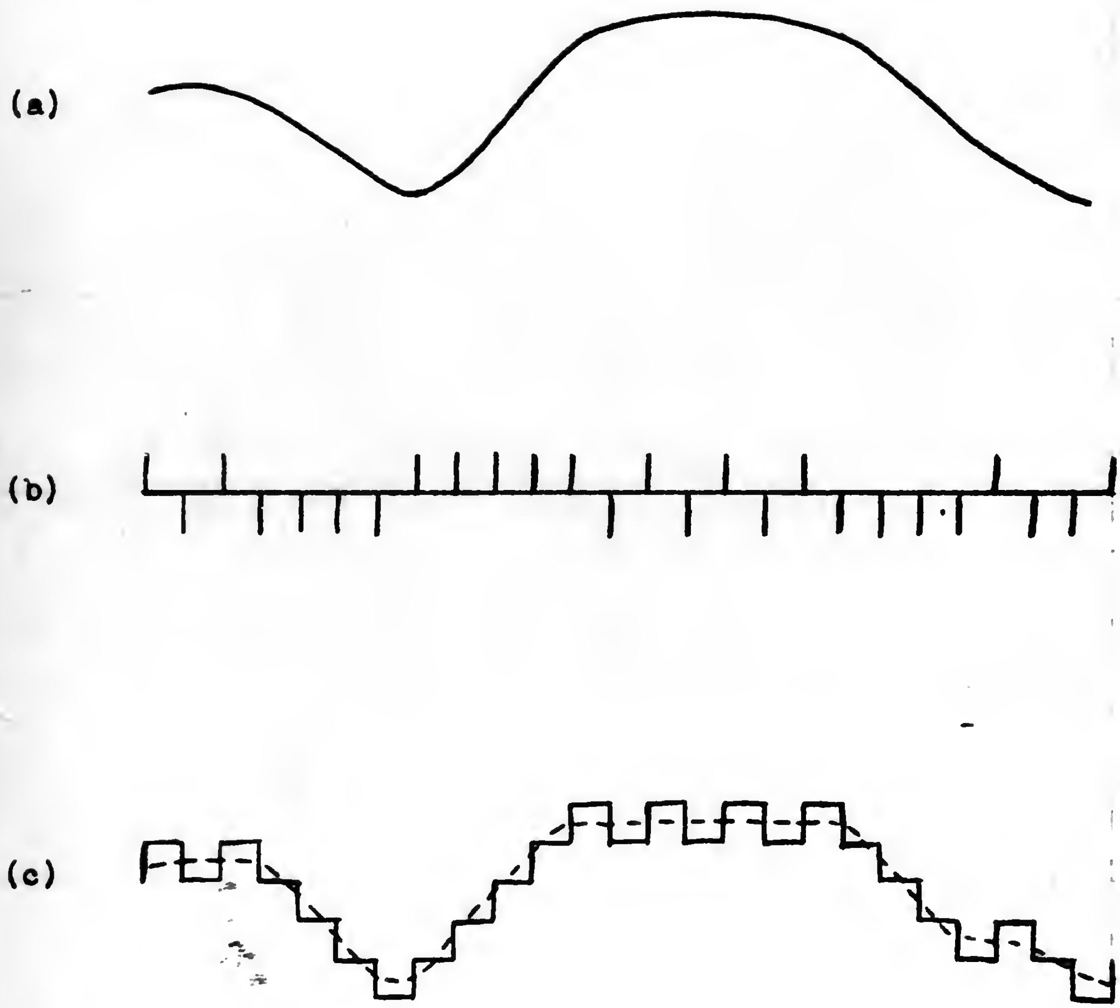

Figure 1. Encoding and Decoding of an Audio Signal Using Polar Pulses and an Integrating Network
(a) Audio Signal F(t)
(b) Encoded Polar Pulses
(c) Output of integrating network (solid lines) showing smoothing effect of low-pass filter (dashed line)

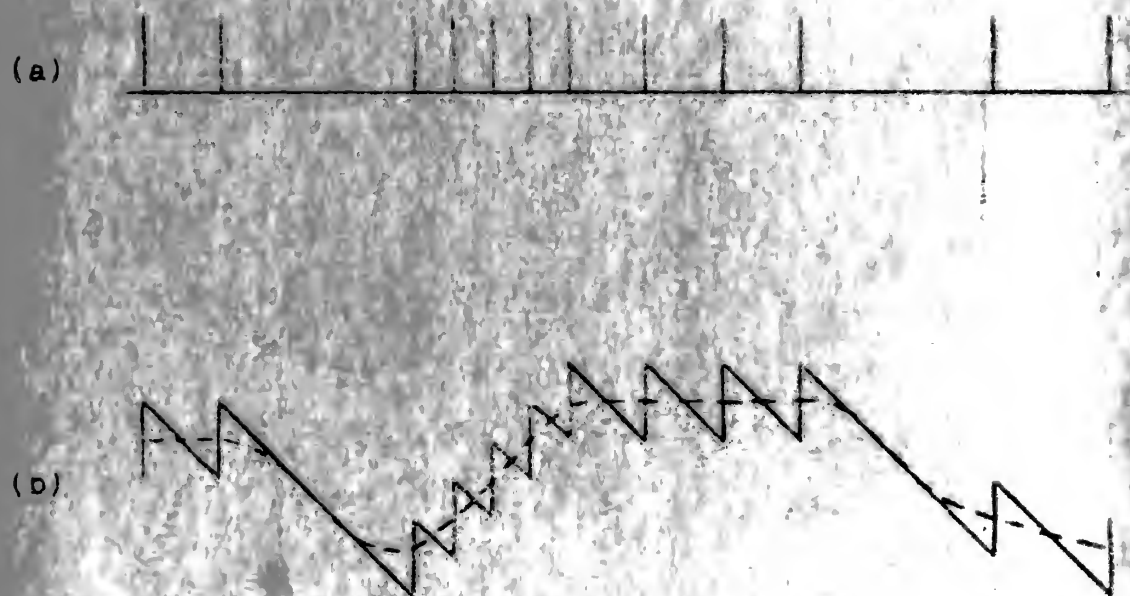

Figure 2. The Audio Signal of Figure 1 Encoded Using Unidirectional Pulses and Decoded with a Modified Integrating Network
(a) Encoded unidirectional pulses
(b) Output of modified integrating network (solid lines) showing smoothing effect of low-pass filter (dashed line)

between two adjacent pulses, the smoothed signal will be identical in both cases.

In the examples given so far no mention has been made of the manner in which the audio signal has been converted into the deltamodulation signal. However, before investigating the method of operation of the coders, it would be well to consider some of the other properties of deltamodulation. It has been stated previously that deltamodulation is a quantized communication system. It is, in fact, quantized both in amplitude and in time. Examples of quantization[5] are shown in figure 3. The quantization in time is a direct result of the sampling technique, since the instantaneous value of the input signal can be observed only at fixed intervals in time. By its very nature, being an intermittent transmission, it is impossible for a pulse modulation system to transmit a continuous signal. The amplitude quantization is not quite so self-evident, but is introduced due to the fact that each pulse represents an increment of constant and unvarying amplitude in the intelligence signal which results in the transmission of a series of values separated by a fixed amount in amplitude.

Bearing in mind the implications of quantization as discussed above, it is possible to consider the process of encoding a signal in deltamodulation from two different viewpoints. The earliest systems[5,7,9] of deltamodulation encoding involved a gated feedback system, in which the output of a pulse modulator was passed through an integrating network, and the output of this network compared to the input audio signal, with the sign of the difference determining the output of the modulator. This system, referred to as the Feedback Method, is applicable to several types of modulators, and is discussed more fully in the following chapter.

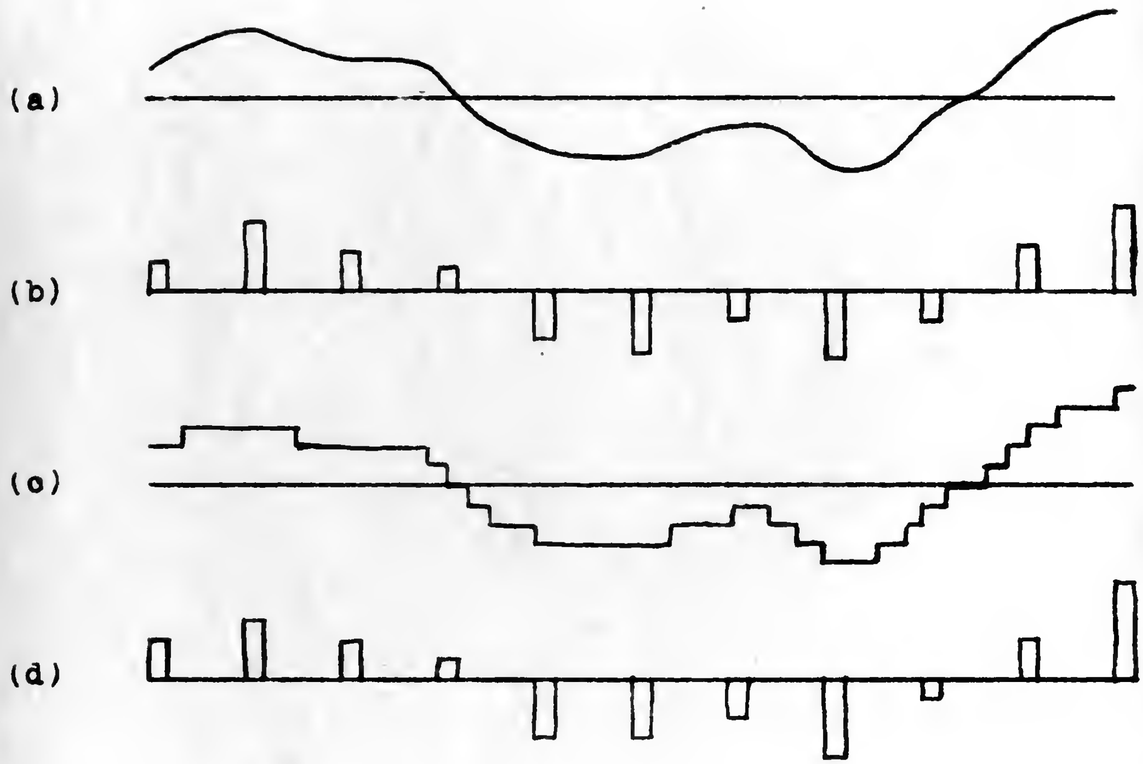

Figure 3. Examples of Quantization
(a) A continuous time function F(t)
(b) F(t) quantized in time but unquantized in amplitude
(c) F(t) quantized in amplitude but continuous in time
(d) F(t) quantized both in time and in amplitude

The other, more recent, method[6] of encoding a signal involves considering the deltamodulation code as a pulse frequency (or pulse density) modulation which is quantized in time. This system uses a variable-frequency pulse generator controlled by the input audio signal so that the frequency of the output is proportional to the magnitude of the derivative of the input signal. The output of this variable-frequency pulse generator is then passed to a type of coincidence network which simultaneously receives a continuous sequence of constant frequency pulses from a timing pulse generator. The coincidence network operates so as to pass only those timing pulses which immediately follow a pulse from the variable-frequency pulse generator, and to eliminate all other pulses. This system, referred to as the Synthesis Method, produces an encoded output which is identical with that of the Feedback Method under normal operating conditions, and has certain advantages over the older system when overmodulated. These features of the Synthesis Method are discussed more fully in Chapter III.

CHAPTER II

FEEDBACK METHOD OF ENCODING A SIGNAL IN DELTAMODULATION

As discussed in the previous chapter the deltamodulation signal may be considered to have been produced either by a gated feedback system or by a time-quantized pulse-frequency modulation system. In this chapter some of the practical circuits for producing deltamodulation by the Feedback Method will be discussed, together with the major advantages and disadvantages of each circuit.

As shown in figure 4, the equipment used in the Feedback Method of encoding a signal in deltamodulation consists of a timing pulse generator, a modulator, a feedback network, and a comparator. The system operation may be simply described as follows: the timing pulse generator produces equally spaced pulses of constant amplitude at the sampling rate chosen for the system. These pulses are then passed or eliminated by the modulator, and the resultant deltamodulation signal is sent to the transmitter and the feedback network. In the feedback network (identical to the decoding network of the receiver) the pulses are decoded and the resultant audio signal is passed to the comparator. Thus the comparator receives two signals; one the input audio signal, and the other the audio signal as it would appear at the output of the receiver. The comparator determines the difference between these two signals; and, depending upon the sign of this difference, enables the modulator to either pass or eliminate the succeeding pulse from the timing pulse generator. The response of the modulator is so arranged that the pulse is passed when the input signal is greater than the feedback signal, and eliminated when the reverse is true. (See figure 5.)

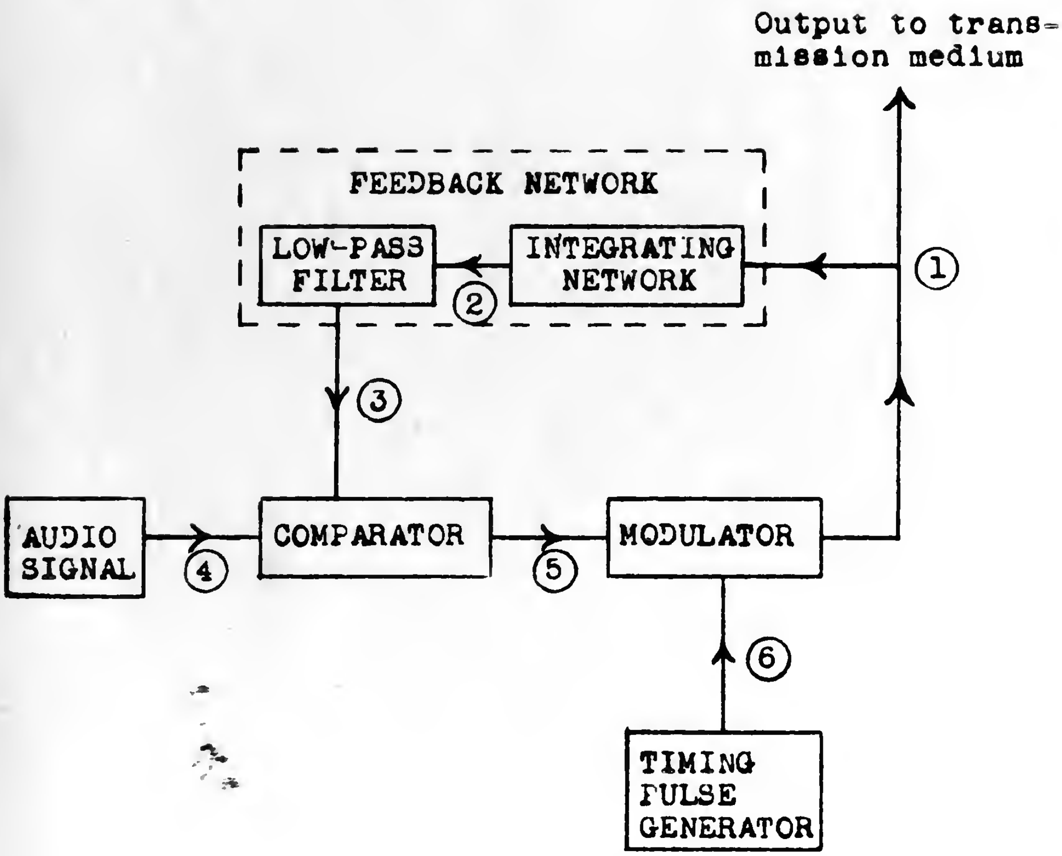

Figure 4. Feedback Method of Encoding a Signal in Deltamodulation (numbers refer to corresponding waveforms in figure 5)

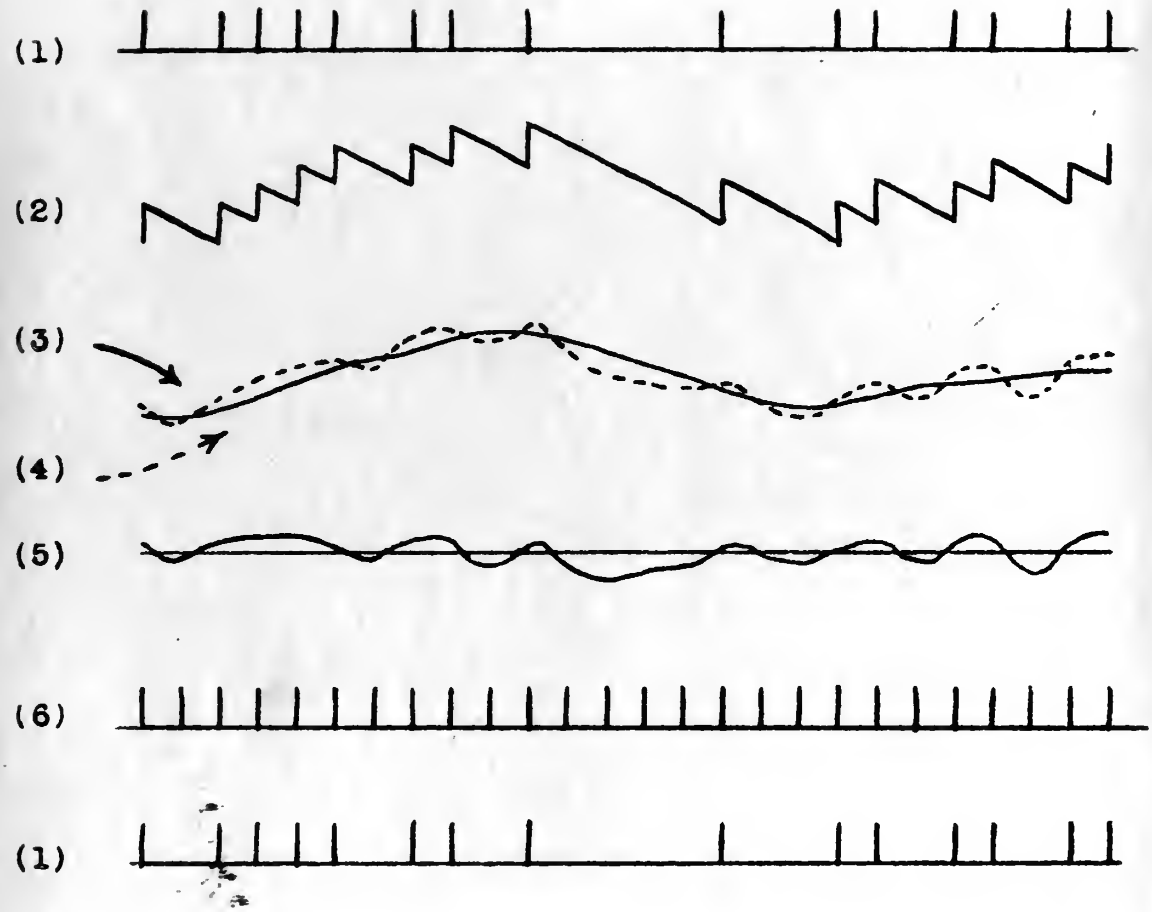

Figure 5. Waveforms in Feedback Method of Deltamodulation
(numbers refer to points in Figure 4)

The principal element of any system using the Feedback Method is the feedback network itself. As discussed in the first chapter of this paper, the majority of practical systems of deltamodulation transmit a signal consisting of a sequence of equally spaced pulses of equal amplitude, with the coding being represented by the absence of certain pulses in the sequence. In order to decode the pulsed output to an audio signal, it is necessary for the feedback network to produce an output voltage which increases by one unit for each input pulse, and decreases by one-half unit during each interval between pulses. (See figure 2.) A pulse-counting network[10], modified by the addition of a pentode operated in a constant current condition to provide the constant current discharge path, will meet the foregoing requirements. A network of this type is shown in figure 6. The input coupling capacitor C_1 is much smaller than the storage capacitor C_2. Upon application of the positive input pulse from the deltamodulation modulator, D_1 conducts, and the value of the pulse voltage is divided between C_1 and C_2 in inverse ratio to the magnitude of their capacitances. At the end of the pulse, C_1 discharges almost immediately through D_2, hence C_1 is ready to receive the next pulse. Between pulses a current flows through V_1 to discharge C_2. Due to the characteristics of the pentode, this current is substantially constant and independent of the voltage on C_2. The bias on V_3 is adjusted so that the current flowing will reduce the voltage across C_2, by a value equal to one-half of the increase produced by one pulse, by the time the next pulse is due to arrive at C_1. In this manner the waveform of figure 2(b) is produced. The resistor R and the capacitor C_3 form a low-pass filter, and the resultant audio-frequency signal is coupled to the comparator stage by C_4.

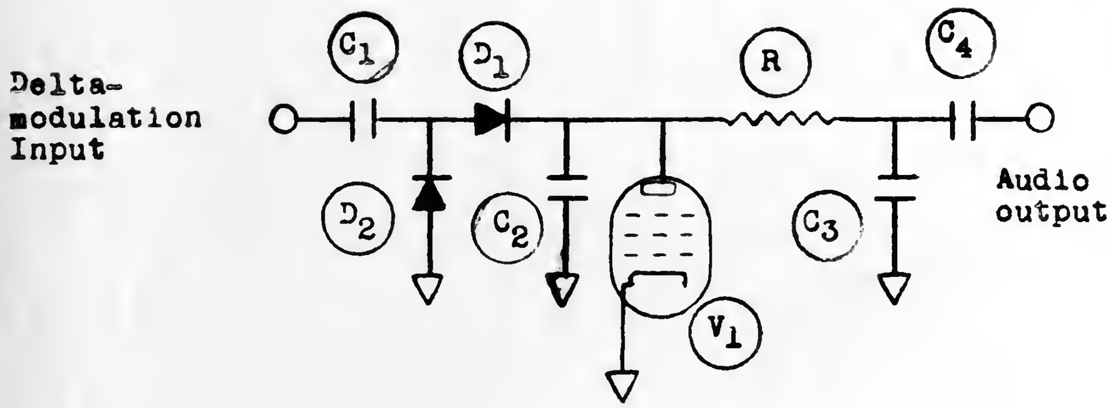

Figure 6. Feedback Network for Use with Deltamodulation Signal

1. Triode Modulator

The most elementary type of modulator involves the use of a triode, with the one tube acting both as comparator and modulator. A typical circuit for a triode modulator is shown in figure 7. In this circuit the values of C_1 and R_g are selected to couple the pulse from the timing pulse generator to the modulator grid. Capacitors C_2, C_3 and C_4 are selected to pass the lowest audio frequency desired, C_4 being the same as the output coupling capacitor C_4 in figure 6, and is shown here only to emphasize its D.C. blocking function. R_g and R_L are the usual grid and load resistors, selected of resistance magnitudes common to the particular triode used in the circuit to ensure proper operation. Values ranging from 50 Kohms to 200 Kohms are typical. The resistors R_1 and R_2 form a voltage divider across the plate voltage supply, so proportioned that, with no output from the feedback network (quiescent condition), the tube will remain cut off even during the application of the pulse from the timing pulse generator. However, for reasons to be indicated, the value of the grid to cathode voltage of the modulator cannot be more than a small increment greater than that necessary to cut off the tube during the period of application of the pulse, hence the adjustment of the circuit becomes quite critical, and the regulation of the timing pulse generator must be very good to ensure proper operation.

During normal operation of the circuit, after equilibrium has been established, there will be audio frequency voltages appearing both at the audio signal input and at the feedback network output. In accordance with the principles of operation of the Feedback Method, as outlined previously, when the feedback network output is greater than the audio

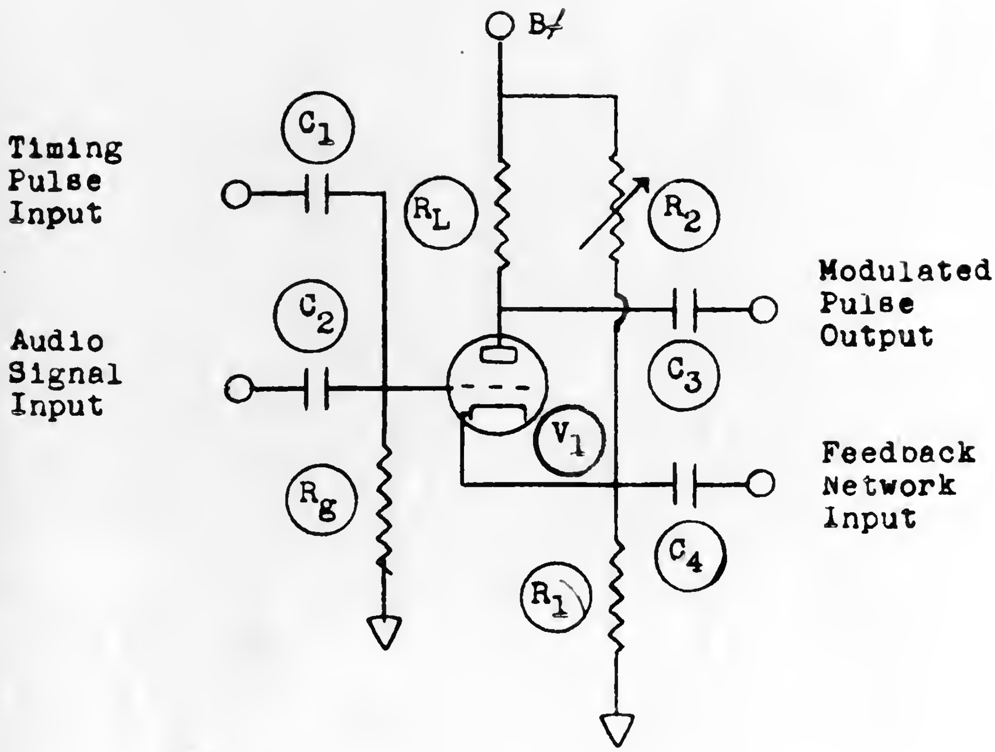

Figure 7. Triode Comparator and Modulator

signal input, there should be no pulse output. This is manifestly true in the triode modulator, since this condition puts the grid even farther beyond the cutoff voltage. Correspondingly, at any time that the audio signal input is greater than the feedback network output, the pulse from the timing pulse generator should be coupled to the output of the modulator. This may be accomplished precisely by the triode modulator circuit only if the peak of the timing pulse is an infinitesimal voltage below cutoff in the quiescent condition, a condition impracticable to maintain in practice due to variations in supply voltage and pulse generator output variations. As a result, depending upon the initial adjustment and the extent of the variations encountered in operation, the triode modulator does not operate as an ideal deltamodulation modulator, but has a slight bias either toward excessive passing or excessive elimination of pulses; the latter condition being the more common due to the method of adjusting the modulator in the quiescent condition. The triode modulator suffers an additional disadvantage in that the amplitude of the output is not a constant, varying with the magnitude of the difference of the signals applied. This necessitates the use of a limiter stage following the modulator to produce pulses of uniform amplitude. In addition, there is little isolation between the input and output circuits of the modulator, which could lead to direct capacitive coupling of the pulse through the modulator, and consequent loss of modulation.

It would appear that the obvious method by which the sensitivity of the triode modulator could be improved without necessitating extremely critical adjustment of the bias voltage would be to amplify

the signal from the feedback network, and to increase the amplitude of the input audio signal. However, since the feedback signal is applied directly to the cathode of the triode, and may be of large amplitude even when not amplified, only a small increase in sensitivity can be effected in this manner before the operation of the tube is changed due to variation of the effective plate supply. It is therefore necessary to look to another type of modulator to increase the accuracy of modulation.

2. Pentode Modulator

The presence of three grid elements in the pentode tube make it possible for the pentode to act as a deltamodulation encoder in a multiplicity of manners. Perhaps the simplest of these methods utilizes the pentode both as comparator and modulator in a manner identical to that used in the triode, except that the pulse input is applied to the screen grid through a cathode follower. A typical circuit using this method is illustrated in figure 8. With the exception of R_k, all of the components in figure 8 must meet the same conditions as for the corresponding components in the triode modulator (figure 7) listed in the preceeding section. R_k is the load resistor for the cathode follower, and in order to provide a relatively low impedance source of voltage for the screen grid, should not greatly exceed a resistance of approximately 20 Kohms. There are several advantages inherent in this circuit over the triode circuit. First, removing the pulse input from the control grid to the screen grid circuit reduces the regulation requirements for the timing pulse generator by a factor equal to the reciprocal of the screen mu of the particular pentode tube chosen. Second, the likelihood of direct capacitive coupling of the pulse through the tube is reduced in two ways: in the pentode the pulse input is of much lower impedance due to the cathode follower coupling; and the suppressor grid acts as a screen to reduce the capacitive coupling between the pulse input to the pentode and the output circuit. This type of pentode modulator suffers from the same difficulty with regard to the setting of the quiescent bias level and sensitivity as the triode modulator, and also requires a limiter stage following the modulator.

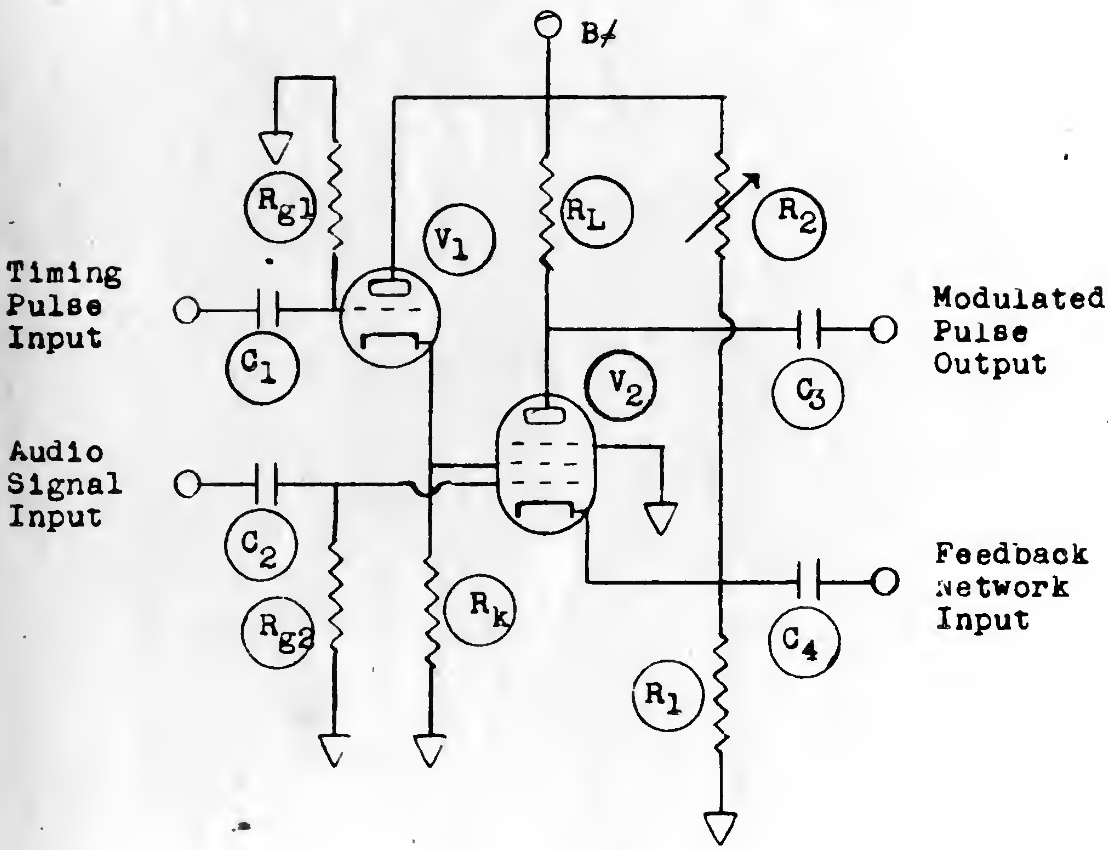

Figure 8. Pentode Comparator and Modulator

In order to utilize the characteristics of the pentode to fullest advantage as a deltamodulation encoder, it is necessary to use a separate comparator stage in advance of the modulator proper, thus making it possible to obtain an amplified difference signal which may be applied directly to one of the modulator grids. The advantage which lies in this process is immediately apparent - since the system operates to maintain the difference between the input and feedback signals as small as possible, this difference will always be smaller than either of the two signals. Hence this difference signal may be amplified by a considerable amount before it is applied to the modulator grid, without encountering difficulty in the modulator. In this manner the accuracy and sensitivity of the modulator may be improved by a factor equal to the gain of the difference amplifier stage. The difference amplifier stage could take several different forms, but since the input signals are always audio-frequency signals, the most logical form for it to take would be that of a push-pull audio amplifier with the two grids fed by the two audio signals to be compared. For this purpose a standard center-tapped push-pull audio transformer could be used as the plate load for the two tubes of the comparator, with the audio input signal going to the grid of one of the tubes, and the output of the feedback network going to the grid of the other, with the difference signal being taken off the output winding of the transformer. However, since the difference voltage will contain signals of a frequency of at least half that of the sampling frequency as a maximum (this occurs only at those times when the slope of the input signal is zero), the so-called "single-ended push-pull amplifier"[8] would seem to be ideally suited to this application, its

transformerless circuitry being more easily and economically designable to provide the required bandpass characteristics, with considerable saving in weight over the iron-cored push-pull output transformer.

A typical circuit of the single-ended push-pull amplifier used as a comparator circuit is shown in figure 9. The fact that an audio transformer (T_1) is required in this circuit to provide isolation for the input to tube V_1 does not invalidate the statement in the previous paragraph as to the saving in weight occasioned by the use of the "transformerless" circuit. This may be seen by considering that T_1 may be a 1:1 ratio transformer designed for low audio frequencies only, which does not have to handle any power or carry any appreciable direct current. Thus it may be much smaller, lighter and cheaper than a push-pull output transformer which has to handle considerable power and direct current, and which must be capable of passing frequencies of the order of 50 Kc. In figure 9, C_1, C_2, and C_3 are audio coupling capacitors. T_1 is a 1:1 ratio audio transformer which provides isolation between the ground-referenced input signal and the grid-to-cathod signal of V_1. R_g is a grid leak resistor of appropriate value in the region of 100-500 Kohms. R_{k1} and R_{k2} are equal resistors for cathode bias so chosen as to be appropriate to the tube type selected for V_1 and V_2, with C_4 and C_5 being identical bypass capacitors for these resistors. Since V_1 and V_2 are identical tubes biased equally by identical bias networks, and are connected in series between the plate voltage supply and ground, the voltage division between the two tubes will be in the same ratio as the values of the plate resistances. Thus with no signal input to either tube, or the same input to both tubes, the voltage drop

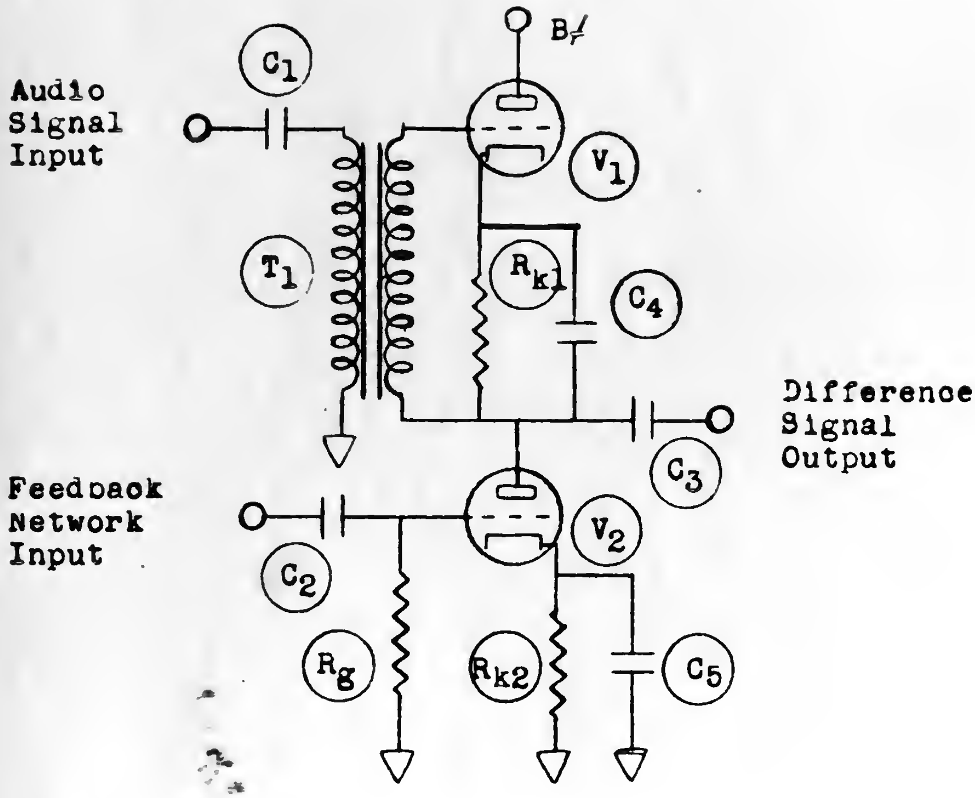

Figure 9. A Single-ended Push-pull Amplifier Used As a Comparator

will be in the same ratio as the values of the plate resistances. Thus with no signal input to either tube, or the same input to both tubes, the voltage drop will be the same across each tube, and the voltage at the plate of V_2 (left hand side of C_3) will be one half of the plate supply voltage. However, if the audio signal input becomes more positive than the feedback network signal, the plate resistance of V_1 will decrease with respect to that of V_2, the voltage drop across V_1 will decrease, and the voltage at the output coupling capacitor will increase, resulting in a positive difference signal output. On the other hand, if the feedback network output becomes more positive than the audio signal input, then the reverse action takes place, resulting in a negative difference signal output.

In the event that the tubes originally selected for V_1 and V_2 were not identical, or become unbalanced while in operation, the resulting effect on the operation of the comparator is not of significant magnitude. This is true for two reasons: (1) The major result of the unbalance would be a change of the direct current voltage level at the plate of V_2, which would not be coupled to the output because of the blocking capacitor C_3. (2) The entire encoder acts as a feedback system to reduce the difference signal at the output of the comparator to zero. Since the sign of the difference, and not its magnitude, is the significant output, a change in the characteristics of one of the two tubes could at most result only in a change of timing of the zero difference transitions. In any case the distortion introduced would be of the same order as the distortion introduced by the inherent quantization of the system.

Having thus produced the difference signal in the comparator circuit, it is now necessary to consider the manner in which this signal is to be applied to the pentode modulator. This may be accomplished in several ways:

it might be applied directly to the control or suppressor grids of the pentode, or it might be applied through a cathode follower (to supply the necessary power gain and impedance transformation) to the screen grid of the pentode. The control grid is the most logical place to apply the pulse input signal from the timing pulse generator, in order to reduce the possibility of direct capacitive coupling of this pulse from the input to output circuits. Application of the difference signal to the control grid is to be discouraged, for reasons discussed relative to the triode modulator with regard to criticallity of pulse generator regulation and bias level at the grid when both the timing pulses and the difference signal are applied to the grid circuit. Application to the screen grid is also to be discouraged since the difference signal will vary in amplitude as well as in polarity, having a detrimental effect on the operating characteristics of the tube. The only remaining possibility is application of the difference signal to the suppressor grid, and this is feasible provided only that the suppressor mu of the tube chosen is sufficiently high to permit cutting off (or nearly cutting off) the tube with reasonable signal level at the input to the comparator circuit. A circuit for a pentode modulator using control grid injection of the timing pulse signal and suppressor grid injection of the difference signal is shown in figure 10. In this circuit C_1 and R_g form a coupling circuit for the timing pulses from the pulse generator, and are selected such that the RC product is long with respect to the pulse width. C_3 is the same capacitor which acts as a D.C. blocking capacitor (C_3 of figure 9) in the comparator circuit. C_3 and R_2 are selected so that the RC product is long with respect to the period of the lowest audio frequency to be handled by the system. Resistors R_1 and R_k are selected to provide the

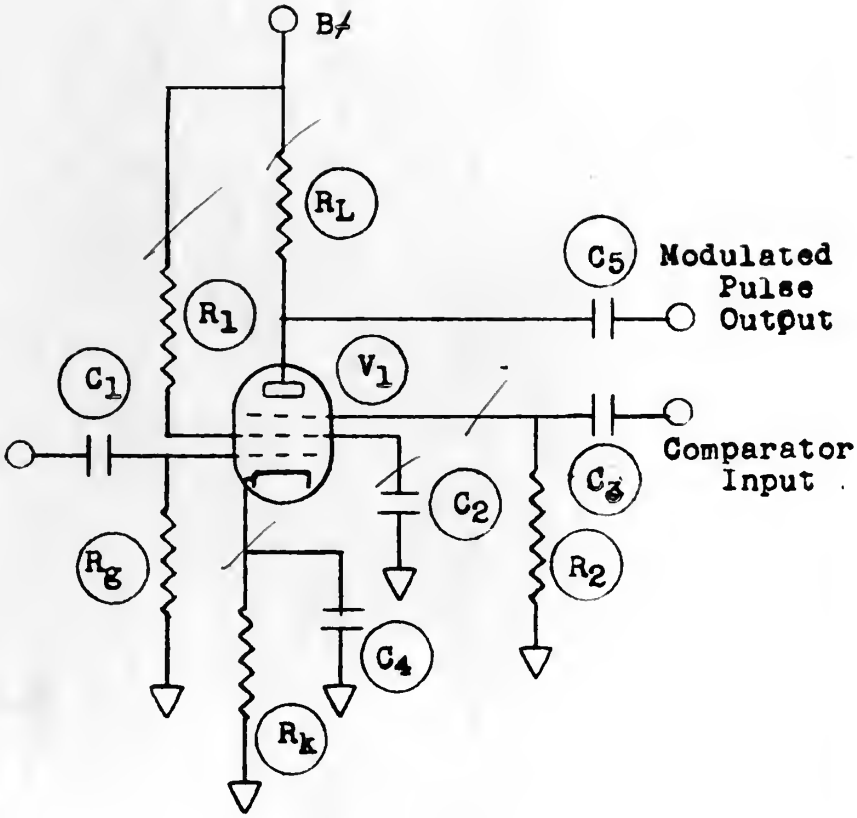

Figure 10. Pentode Modulator

necessary screen and cathode bias voltages for the tube selected, with capacitors C_2 and C_4 acting as audio bypasses. The use of the dropping resistor to provide the screen voltage is important to the proper operation of the circuit, since the screen current increases when the suppressor grid reduces the plate current, and operation of the screen from a fixed voltage source could lead to excessive screen heating during prolonged periods of plate current cutoff, such as occur on the trailing edge of a low-frequency sine wave. The advantages of this type of modulator are easily determined: (1) the likelihood of unintended coupling of the pulse to the output through tube capacity is considerably reduced due to the fact that there are two grids interposed between the pulse signal grid and the plate; (2) the regulation of the pulse generator has relatively little effect on the accuracy of the modulated output, being able to affect only the magnitude of the individual pulses, not the presence or absence of pulses in the output; and (3) the sensitivity of the modulator is limited only by the amount of amplification which has been applied to the difference signal. Due to the fact that the comparator output varies in magnitude, the pulse output of the modulator will also vary, and a limiter stage is necessary to maintain a constant amplitude of output. Depending upon the particular tube type chosen, and the values of bias voltage and suppressor grid leak resistance (R_2') selected, the pentode modulator may or may not have a bias toward excessive or insufficient pulse production. By judicious juggling of these components it should be possible to produce a perfect modulator in this respect, but this would not be a stable condition, since any variation in the tube or components occasioned by aging would disrupt the equilibrium.

3. Gated-Beam Tube Modulator

The gated-beam tube is in effect a special type of pentode, although its construction differs materially from that of an ordinary pentode, in that the current through the tube is formed into a beam and passed through controlling grids which are electro-statically shielded from the cathode. The advantages of the gated-beam tube lie in the characteristics of the limiter (control) and quadrature (suppressor) grids. These grids have extremely high effective transconductances, and either grid may take complete control of the plate current provided only that the other grid is positive by several volts with respect to the grid controlling the current. This control, however, extends over a very limited voltage range, with the tube being cut off when the controlling grid is more than two volts negative, and plate current saturation occuring when it is more than three or four volts positive. This is due to the fact that the controlling grids are nearly completely shielded from the cathode, with the maximum plate current that can flow being determined by the potential of the accelerator (screen) grid. Thus either of the controlling grids can reduce or cut off this current, but neither can increase it. With these characteristics in mind, it can be seen that the gated-beam tube would make a very sensitive deltamodulation encoder in a pentode type circuit such as that in figure 10. In this case the limiter grid would hold the plate current off except when the timing pulse was applied, and the quadrature grid would either saturate or cut off the plate current except for a very narrow range of five or six volts in the neighborhood

of cathode potential, in which region a fraction of the saturation current would flow. However, assuming that there has been considerable gain in the comparator stage preceeding the modulator, there would be very few times that the quadrature grid voltage would fall in this region, and it should be possible to operate this modulator without a limiter stage following.

4. Polar Pulse Modulator

The use of polar pulses in the majority of theoretical considerations of the deltamodulation systems has been mentioned previously. In order to demonstrate the complexity of circuits involving this technique, a practical deltamodulation encoder[3] using the polar pulses is illustrated in figures 11 and 12. The block diagram of this system would be that of the typical feedback system (figure 4), but since the output pulses are polarized, the waveforms at points (1) and (2) would resemble waveforms (b) and (c) respectively of figure 1, rather than the corresponding points of figure 5. Furthermore, the feedback network involved is a true integrating network, requiring as the input polar pulses of current corresponding to the polar pulses of voltage produced by the modulator. The feedback network used in the polar pulse system is shown in figure 11. In this circuit the RC product of R_{12} and C_5 is very long with respect to the interval between successive pulses. The voltages applied to V_2 and V_3 are adjusted so that both tubes are cut off in the quiescent condition between pulses. With no pulses applied to the circuit the voltage across C_5 would be that between the tap on R_{12} and ground, due to the current from the plate power supply to ground through R_{12}. If a positive pulse is applied to the grid of V_1, the grid of V_2 is driven more negative, resulting in no change, since this tube is already cut off. However, the grid of V_3 is driven positive simultaneously, and V_3 conducts, decreasing the charge on C_5 by a given increment. Due to the large time constant of C_5 and R_{12}, this increment of charge will not leak off to any appreciable extent by the time the next pulse arrives at the grid

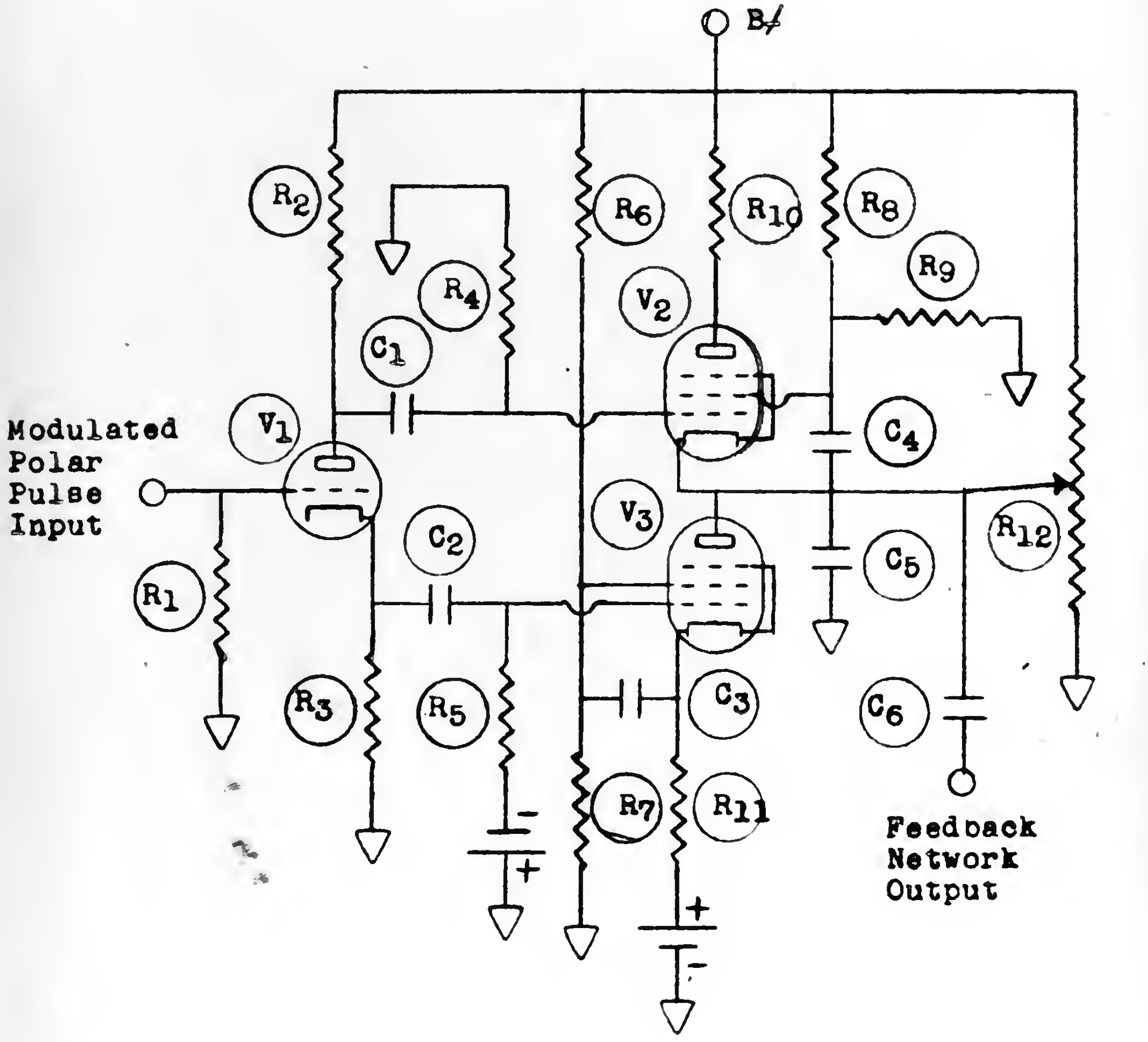

Figure 11. Feedback Network for Polar Pulse Modulator

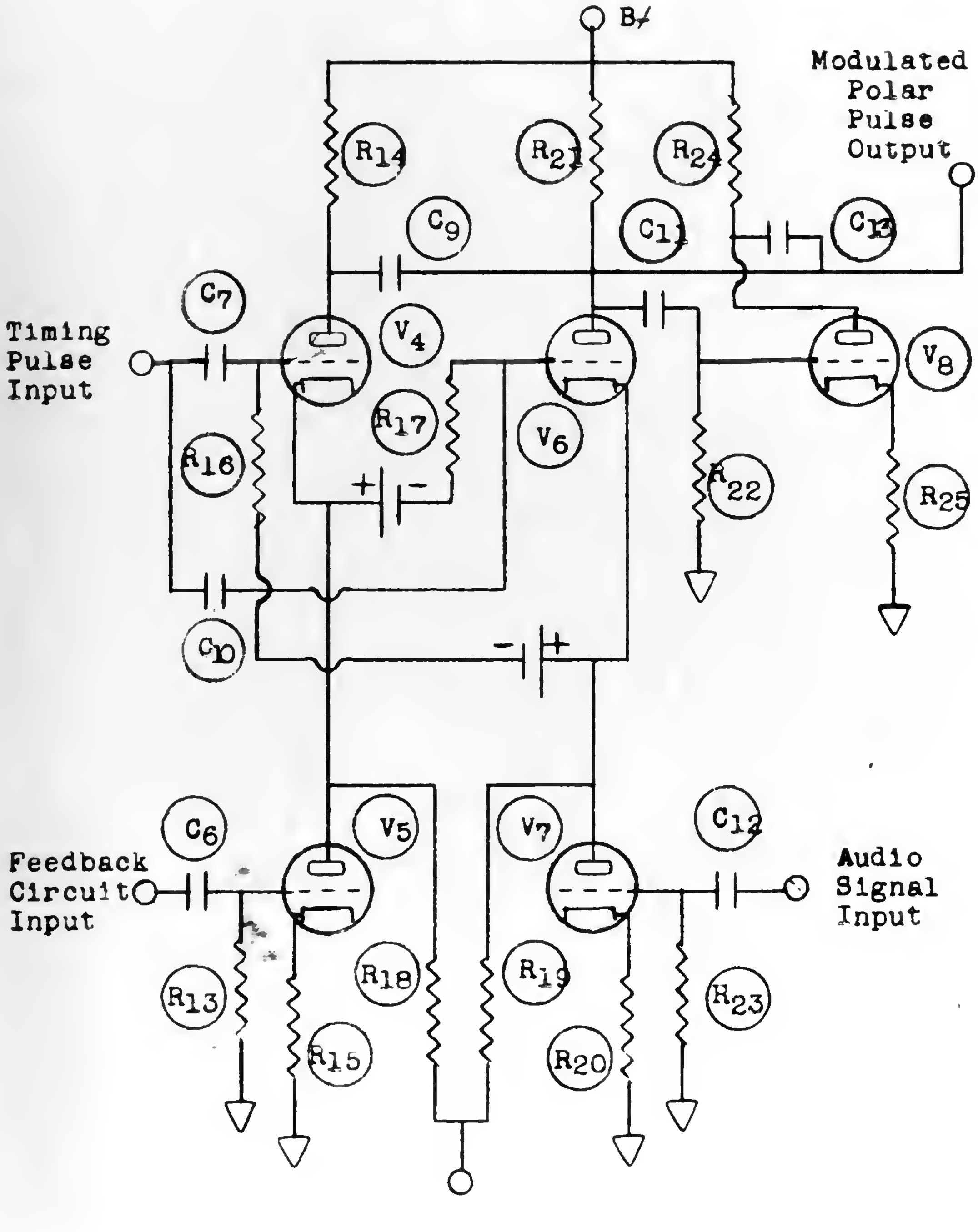

Figure 12. Polar Pulse Modulator

of V_1. For a negative pulse input at the grid of V_1, the opposite action takes place, V_2 conducts and increases the charge on C_5 by a given increment. Thus it is possible for C_5 to integrate current pulses applied to it from V_2 and V_3, and the resulting voltage variations may be coupled to the modulation circuit by C_6.

In the polar pulse modulator itself (figure 12), the voltages applied are so adjusted that with equal inputs to V_5 and V_7, both V_4 and V_6 are cut off even when the timing pulse is applied to their grids. However, if the signal applied to V_5 from the feedback network is greater than that applied to V_7 from the audio input, V_6 will remain cut off, but V_4 will conduct when the pulse input is applied, resulting in a negative pulse at the pulse output. Conversely, if the input to V_7 is greater than that to V_5, V_4 will remain cut off, but V_6 will conduct when the timing pulse is applied, producing a negative pulse at the grid of V_8, which results in a positive pulse at the pulse output.

In addition to the very apparent additional complexity of the polar pulse system over the other types of encoders discussed, there is the disadvantage that the system sends neither positive nor negative pulses for signals of zero slope with respect to time, since in this condition both the modulator tubes are cut off.[3] This results in a lack of differentiation between a lost signal and a signal of zero slope, since both result in the same effect - no pulses. Thus it would be impossible for the operator to determine whether the loss of signal was due to an interruption in the modulation at the transmitter, or to an interruption in the transmission path.

CHAPTER III

SYNTHESIS METHOD OF ENCODING A SIGNAL IN DELTAMODULATION

In the Feedback Method, previously discussed, the processes of quantizing the input signal in amplitude and in time are done simultaneously in the modulator by passing or rejecting the pulse from the timing pulse generator in accordance with the difference voltage between the input signal and the decoded output signal. In the Synthesis Method, however, no decoding of the output or comparison of any sort is necessary.[6] A block diagram of the system is shown in figure 13, with the principal waveforms illustrated in figure 14. In this method, the audio input signal is differentiated, and the resultant voltage used to determine the instantaneous frequency of a variable frequency pulse generator, the frequency output being at all times proportional to the magnitude of the derivative. The resulting frequency-modulated (or density-modulated) pulse signal is then fed into a coincidence network along with timing pulses from a constant-frequency timing pulse generator, and the resulting output is a deltamodulation signal. Since deltamodulation may be thought of as pulse density modulation quantized in time[6], the output of the variable-frequency pulse generator might be referred to as deltamodulation pulses quantized in amplitude but unquantized in time. The signals at this point have the characteristics of deltamodulation with regard to their density and amplitude, but the spacing between pulses is continuously variable, rather than being an integral multiple of a given interval as in the fully quantized deltamodulation signal. Thus the use of the timing pulse generator and the coincidence network

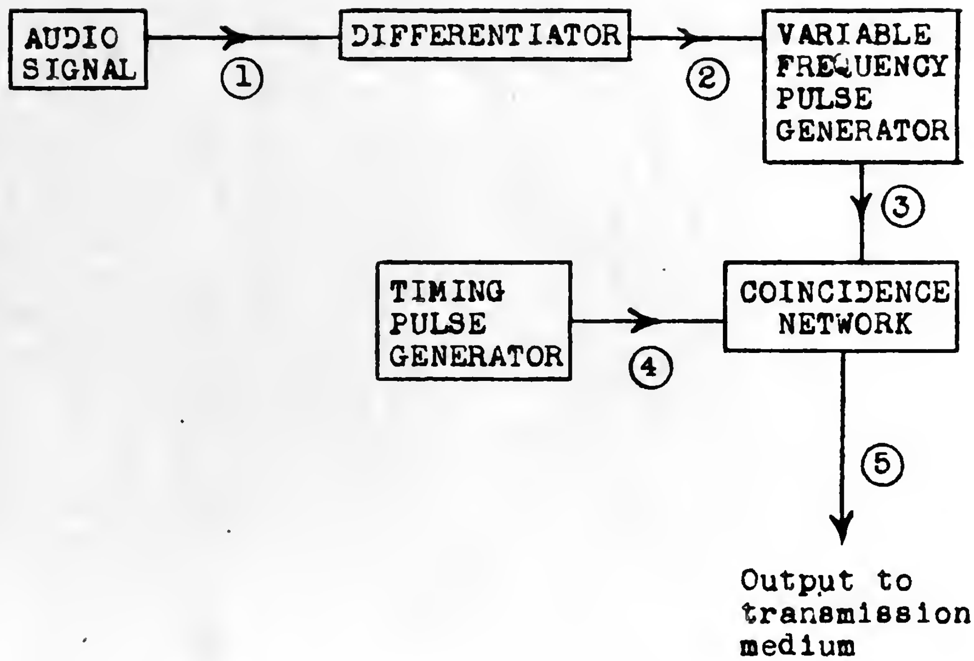

Figure 13. Synthesis Method of Encoding A Signal in Deltamodulation (numbers refer to waveforms in figure 14)

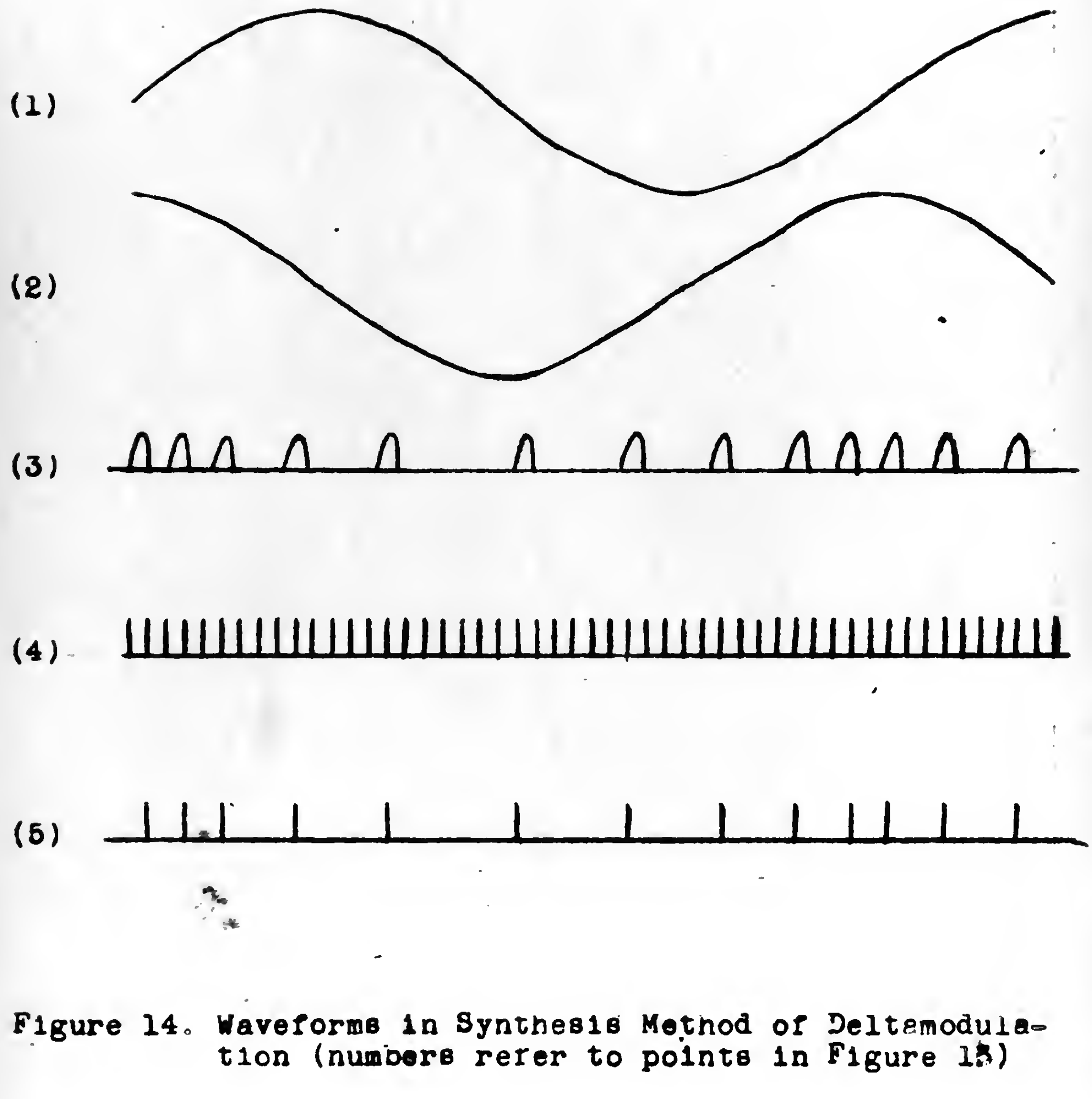

Figure 14. Waveforms in Synthesis Method of Deltamodulation (numbers refer to points in Figure 13)

is necessary to quantize the signal in time. In figure 14 this has been accomplished by passing to the output only those pulses from the timing pulse generator that immediately follow a pulse from the variable-frequency pulse generator. Since only pulses from the timing pulse generator are seen at the output, and these pulses are separated by a fixed interval determined by the frequency of the timing pulse generator, the quantization in time has been achieved.

It has been shown[6] that the deltamodulation signal produced by the Synthesis Method is indistinguishable from that produced by the ideal Feedback Method, except under conditions of overmodulation; and that the equipment using the Synthesis Method will recover from the effects of overmodulation instantaneously, whereas the equipment using the Feedback Method will be disrupted for a finite amount of time after the end of the overmodulation, due to the time lag introduced by the feedback network. In order for there to be an exact equivalence between the outputs of the two systems, it is necessary for the following conditions to be met in the equipment using the Synthesis Method: (1) The frequency of the timing pulse generator must be at least twice the highest frequency (f_{max}) produced by the variable-frequency pulse generator under maximum modulation conditions; and (2) the frequency of the variable-frequency pulse generator must vary from essentially zero to f_{max} under maximum modulation conditions.[6] Both conditions may be easily met by proper adjustment of the circuit parameters.

A practical circuit of a modulator which uses the Synthesis Method of producing deltamodulation is shown in figure 15. V_1 is a triode operated as a blocking oscillator which produces only a single pulse

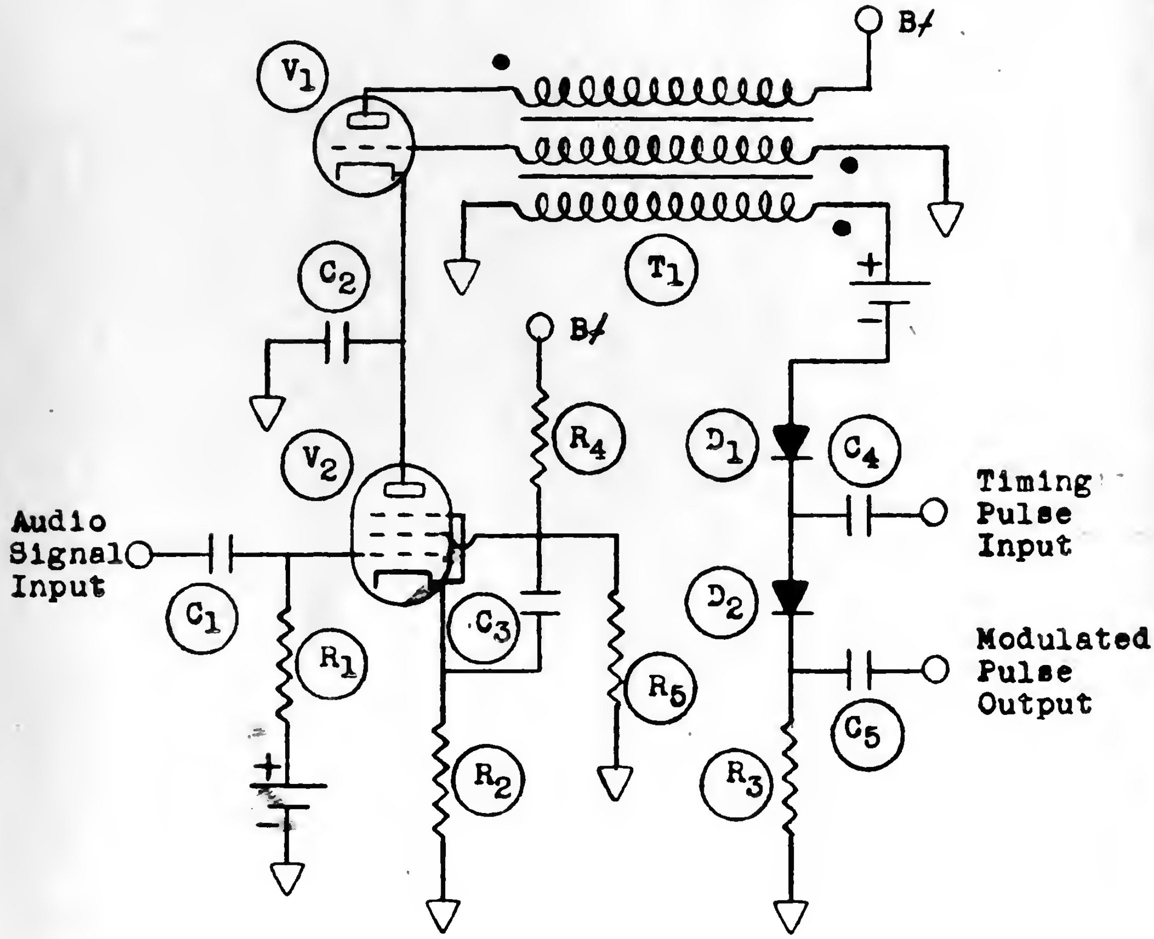

Figure 15. Quantized Pulse-Frequency Modulator

output for each operating cycle. The off-period of the blocking oscillator is a function of the time of discharge of condenser C_2, which is determined by the conduction of the pentode V_2, which is in turn determined by the value of the signal at its grid. The signal at the grid of V_2 is the result of the audio input signal being differentiated by C_1 and R_1. At one extreme the signal at the grid of V_2 could be such as to cut off the pentode, making the off-period of the blocking oscillator infinite, or its frequency zero. At the other extreme, the signal could be such as to saturate the pentode, resulting in the shortest off-period or the highest frequency (f_{max}), with intermediate values between these extreme conditions. Thus the instantaneous frequency of the blocking oscillator would be proportional to the derivative of the input audio signal, and would vary from zero to f_{max}. The output from the blocking oscillator is taken from a third winding on transformer T_1 so oriented that its output is a positive pulse. Two diodes are connected in series with this winding, with the output of the timing pulse generator being injected between the two diodes, and a bias applied to the circuit so that the diode D_2 can conduct only if the timing pulse occurs simultaneously or very shortly after the pulse from the variable-frequency pulse generator. Thus the pulse density modulation is quantized in time, and a true deltamodulation signal results.

The simplicity of the equipment used in the Synthesis Method is quite apparent, especially when it is considered that only two relatively non-critical vacuum-tube circuits are involved: a pentode used[2,5] as a constant-current device, and a triode used in a blocking oscillator.

In addition, the quantized pulse-frequency modulator does not exhibit the bias towards excessive or insufficient pulse production characteristic of feedback modulators, and should be capable of any degree of accuracy desired.

CHAPTER IV

COMPARISON OF DELTAMODULATION ENCODERS

In order to make a fair comparison between the different types of encoders which may be used to produce a deltamodulation signal, it is necessary to take into consideration several different and not necessarily related factors. The principal factors to be considered are the following: (1) Sensitivity, which is an inverse measure of the amplitude of the signal which must be applied to the modulator to ensure its proper operation, (2) Accuracy, which is a measure of the correspondence between the decoded output of the modulator, and the audio signal input to the modulator, assuming a fixed sampling rate for all modulators, (3) The effect on subsequent output of a signal which produces overmodulation (in this connection it is to be understood that none of the modulators will operate properly during overmodulation conditions), (4) The magnitude of effect produced by direct capacitive coupling from pulse input to pulse output, (5) The effect of poor regulation in the timing pulse generator, (6) Whether a limiter stage must be utilized following the modulator to ensure constant amplitude pulses, and (7) The number of vacuum tubes required to perform the function, which is an inverse measure of the reliability of the circuit.

Since the exact values of several of the factors to be considered would depend upon the individual circuit values and the individual tube or tubes chosen, only an approximate qualitative comparison can be made. In view of this, and the number of factors to be compared, it is felt that the best comparison can be made in the form of a table, in which the

Table I

Factor	Type of Modulator: Triode Comparator and (1) Modulator	Pentode Comparator and (1) Modulator	Pentode Modulator (1)(2)	Gated-Beam Tube Modulator (1)(2)	Polar Pulse Modulator (1)	Quantized Pulse-Frequency Modulator
Sensitivity	low	low	high	high	high	high
Accuracy	low	low	high	high	high	high
Effect of Overmodulation	prolonged	prolonged	prolonged	prolonged	prolonged	instantaneous
Direct Capacitive Coupling	large	small	negligible	negligible	large	negligible
Effect of Timing Pulse Generator Regulation	large	small	large	large	large	small
Limiter Stage Required	Yes	Yes	Yes	No	Yes	No
Tubes Required(3)	1 Pentode 2 Triodes	2 Pentodes 2 Triodes	2 Pentodes 3 Triodes	1 Pentode 3 Triodes 1 Gated-Beam	2 Pentodes 7 Triodes	1 Pentode 1 Triode

NOTES:
(1) Used with the appropriate Feedback Network
(2) Require the use of a Comparator stage
(3) Includes the tubes necessary for the feedback network and comparator, if required, but does not include the timing pulse generator which is common to all modulators

various factors can be seen simultaneously. This has been done in Table I. Each of the factors considered in this table has been discussed in the section dealing with each individual modulator. No account is taken of the characteristics of the timing pulse generator, since this equipment has not been specified, and could be the same for all modulators.

In the preceeding table the desireable features of each factor considered have been underlined in red for easy identification. Upon examination of the table it becomes apparent that there is only one modulator which has a desireable characteristic in all of the factors, and that is the Quantized Pulse-Frequency Modulator which uses the Synthesis Method of encoding a signal in deltamodulation. It would therefore appear that this is the best type of modulator which has come to the attention of the author, and that it holds considerable promise as a compact, rugged and reliable encoder for deltamodulation transmission systems.

BIBLIOGRAPHY

1. E.G. Beard; Some notes on time division telephony and methods of pulse modulation; Proc J Instn Radio Engrs Aust 11, 14-16, January 1950, J Brit Instn Radio Engrs 10, 242-243, July 1950

2. W.R. Bennett; Spectra of quantized signals; Bell Sys Tech J 27, 446-471, 1948

3. E.E. Deloraine, S. van Mierlo, and B. Derjavitch; Communication system utilizing constant amplitude pulses of opposite polarity; French Patent 932,140 of 10 August 1946, U.S. Patent 2,629,857 of 24 February 1953

4. N.R. French and J.C. Steinberg; Intelligibility of speech; J Acoust Soc Amer 19, 90-119, January 1947

5. F. de Jager; Deltamodulation, a method of PCM transmission using the 1-unit code; Philips Research Reports 7, 442-466, December 1952

6. Laboratoire Central de Télécommunications, Paris, France; Note on deltamodulation; Elect Commun 30, 71-74, March 1953

7. L.J. Libois; Un nouveau procede de modulation codée "la modulation en Delta"; L'Onde Elect 32, 26-31, January 1952

8. A.P.G. Peterson and D.B. Sinclair; A single-ended push-pull amplifier; Proc Inst Radio Engrs 40, 7-11, January 1952

9. J.F. Schouten, F. de Jager, and J.A. Freefkes; Deltamodulation, a new modulation system for telecommunication; Philips Tech Tijdschr 13, 249-258, September 1951, Philips Tech Rev 13, 237-245, March 1952

10. U.S. Navy Department, Bureau of Ships; Radar Electronics Fundamentals; Government Printing Office, Washington, D.C., June 1944

Irving
Encoders for deltamodulation transmission systems.

Irving
Encoders for deltamodulation transmission systems.